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OPTIMIZATION OF THE RANGE OF
ELASTIC BEHAVIOR OF UNIDIRECTIONAL
COMPOSITES BY PRESTRAINING

R. W. Heckel, R. J. Zaehring,
and H. P. Cheskis



Technical Report No. 5

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# OPTIMIZATION OF THE RANGE OF ELASTIC BEHAVIOR OF UNIDIRECTIONAL COMPOSITES BY PRESTRAINING

R. W. Heckel*, R. J. Zaehring**, and H. P. Cheskis***

## ABSTRACT

The effect of tensile prestrain on the stage I tensile yield stress has been studied both analytically and experimentally for composites whose stress-strain curves obey the rule of mixtures. The mathematical analysis provides a means for calculating the optimum amount of prestrain, the residual stresses (in the direction of the fibers) in the matrix and fiber materials after unloading from the prestraining, and the stage I yield stress in the composite after the prestrain treatment. It is shown that the improvement in stage I yield stress by prestraining is due to the development of negative residual stresses in the matrix. The stage I yield stress in composites with negligible residual stresses in the as-fabricated condition can usually be improved by a factor of two by prestraining; the amount of improvement is even greater if the as-fabricated composites have the usual state of residual stress, i.e., tension in the matrix. Experimental studies on 2024 aluminum-tungsten composites (filament-wound; hot-pressed) having tungsten fiber volume fractions between 0.08 and 0.40 verified the mathematical analysis. The stage I yield stresses measured in these composites after a prestrain of $4.2 \times 10^{-3}$ were in good agreement with predicted values. Improvements of up to a factor of six were found in the stage I yield stress as a result of prestraining.

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## INTRODUCTION

Fiber reinforced composites containing less than 0.50 volume fraction of fibers ($V_f$) usually have stage II (matrix-plastic; fiber-elastic) moduli which are significantly lower than the stage I (matrix and fiber both elastic) moduli. Thus, composite structural design is encumbered with a double modulus consideration. In addition, prediction of the onset of stage II (i.e., stage I yield point ($\sigma_I$)) is difficult because residual stresses which are developed in the composite because of differences in thermal and flow properties of the matrix and fibers (1-6) can shift the stage I yield point (7-9). One solution to the problem is to increase $V_f$ to a high enough level where the difference between the stage I and II moduli can be neglected in design considerations. The present costs of reinforcing fibers, however, make this solution rather costly. Another solution to the problem is to tailor the residual stresses in the matrix and the fibers and thereby optimize the elastic behavior of the composite.

It has been shown experimentally (7,8) that negative matrix residual stresses increase $\sigma_I$, since the range of strain over which the matrix behaves elastically is increased. In addition, it was demonstrated that the effects of residual stresses could be treated analytically by considering the residual stresses in terms of previously applied elastic strains for both the matrix and the fibers. The behavior of the overall composite was found to correspond to rule-of-mixtures addition of the stress-strain curves of the matrix and the fibers after they were corrected for their respective amounts of residual strain.

The range of elastic behavior (i.e., $\sigma_I$) of continuous-fiber, unidirectional composites may, therefore, be improved by processing which provides a negative residual stress in the matrix. This may be accomplished by small amounts of tensile prestrain on the composite (7-9). The effect of tensile prestrain on subsequent

stress-strain behavior of the matrix and fibers has been analyzed by Baker and Cratchley (6) in their work on composite fatigue behavior. Their analysis considers the balance of forces between the matrix and fibers after cyclic tensile deformation of the composite. Upon unloading the composite after tensile loading into the stage II region, the remaining stress in the fibers was sufficient to cause the matrix to yield in compression. At zero applied load on the composite, a balanced force condition existed in the composite with the matrix remaining in compression and the fibers remaining in tension. Reloading the composite in tension resulted in an extended elastic region of the composite because of the residual compressive strain in the matrix.

It is the purpose of this paper to define a prestrain analysis that may be used to improve the value of $\sigma_I$ for continuous-fiber, unidirectional composites that are to be stressed in tension*. The analysis will be shown to be a function of each of the components of the composite. This paper will also include experimental verification of the analysis with composites of 2024 aluminum (matrix) and tungsten (fiber) with fiber volume fractions between 0.08 and 0.40.

## ANALYSIS

The prestrain analysis to be developed is based upon the fact that tensile stresses greater than the stage I yield stress, $\sigma_I$, in composites where the modulus of the fiber is greater than that of the matrix ($E_f > E_m$), will, on unloading, cause compressive residual stresses in the matrix ($\sigma_m^R$ = -) and tensile residual stresses in the fibers ($\sigma_f^R$ = +). After this tensile prestrain, the stage I yield stress in tension, $\sigma_I^P$, will be increased because of the increased range of strain over which

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*The analysis is also applicable to compression. However, improved $\sigma_I$ values in compression result from the development of positive residual stresses in the matrix by compressive prestrain prior to the application of compressive loads.

the matrix will be elastic. The purpose of the present analysis is to provide a means for defining the optimum amount of tensile prestrain, $e_s$, and the resulting stage I yield stress, $\sigma_I^p$, as a function of the properties of the matrix and fiber components (moduli, $E_m$ and $E_f$; yield stresses, $\sigma_m^y$ and $\sigma_f^y$; fiber fracture stress, $\sigma_f^F$; as-fabricated residual stresses in the direction of the fibers, $\sigma_m^{RO}$ and $\sigma_f^{RO}$) and the volume fraction of fibers, $V_f$. The analysis will assume that the rule-of-mixtures is applicable if residual stresses are accounted for, work hardening is negligible, lateral stresses are negligible, and stresses in each component are uniform. Prior experimental studies (7-9) have shown the first assumption to be applicable to composites with fiber volume fractions of about 20 to 30 percent. The other assumptions should be valid in the present analysis since the range of strains of interest is quite small. In addition, the analysis assumes that the yield stress of the matrix in compression is equal to the negative of that in tension. This assumption, although reasonable, may be critical in some composite systems; the experimental studies on composites in the present research indicate that this assumption is certainly reasonable.

The maximum compressive residual stress in the matrix which may be developed by tensile prestraining is assumed to be $-\sigma_m^y$. However, it may not be possible to achieve this value if the fibers fracture or deform plastically during the tensile prestraining. The maximum tensile stress that may be applied to the fibers will be designated as $\sigma_f^{max}$ (either the fracture or yield stress, whichever occurs first). Thus, for a composite containing a given volume fraction of fibers ($V_f$), the maximum compressive residual stress in the matrix will be developed by tensile prestraining the composite up to $\sigma_f^{max}$. If the values of $\sigma_f^{max}$ and/or $V_f$ are relatively low, the compressive residual stress in the matrix may be less than $|-\sigma_m^y|$. If the values of $\sigma_f^{max}$ and/or $V_f$ are relatively high, the matrix will yield in compression following the tensile prestrain and the compressive residual stress in the

matrix will be $-\sigma_m^{\ y}$.

The Critical Volume Fraction

It is useful at this point to define the critical volume fraction, $V_f'$, for which tensile prestraining up to $e_s$, the strain necessary for $\sigma_f^{max}$, achieves a compressive residual stress in the matrix of $-\sigma_m^{\ y}$ without compressive plastic deformation. The stress-strain behavior for such a composite as determined by the rule-of-mixtures and the behavior of the matrix and fibers is shown in Figure 1, where $e_p$ is the total plastic strain of the composite brought about by prestraining. Balance of forces and the rule-of-mixtures dictate that at $e_p$:

$$\sigma_m^{\ R}\cdot(1-V_f) + \sigma_f^{\ R}\cdot V_f = 0 \qquad (1)$$

where $\sigma_m^{\ R}$ and $\sigma_f^{\ R}$ are the residual stresses in the matrix and fiber, respectively, after prestraining by $e_s$ and subsequent unloading to $e_p$.

Since $\qquad \sigma_m^{\ R} = -\sigma_m^{\ y}$

$$-\sigma_m^{\ y}\cdot(1-V_f) + \sigma_f^{\ R}\cdot V_f = 0 \qquad (2)$$

The value of $\sigma_f^{\ R}$ can be found geometrically from Figure 1 to be:

$$\sigma_f^{\ R} = \sigma_f^{max} - E_f\cdot(e_s-e_p) = \sigma_f^{max} - E_f\cdot\frac{2\sigma_m^{\ y}}{E_m} \qquad (3)$$

Substitution of Equ. 3 into Equ. 1 then defines $V_f = V_f'$ as:

$$V_f' = \frac{1}{1 + (\sigma_f^{max}/\sigma_m^{\ y}) - 2(E_f/E_m)} \qquad (4)$$

It should be noted that Equ. 4 is independent of the original residual stresses in the composite, $\sigma_f^{\ RO}$ and $\sigma_m^{\ RO}$. The dependence of $V_f'$ on $\sigma_f^{max}/\sigma_m^{\ y}$ and $E_f/E_m$ is shown in Figure 2.

Figure 1 indicates that reloading of the composite of $V_f = V_f'$ after prestraining begins at $e_p$ with the matrix stress at $\sigma_m^{\ R} = -\sigma_m^{\ y}$. The stage I yield stress of the composite on reloading occurs at the strain necessary to cause matrix yielding, $e_I^P$ (total strain relative to the composite prior to prestraining), which in this

instance is equal to $e_s$. The prestraining is therefore seen to improve the stage I yield stress of the composite from $\sigma_I$ to $\sigma_I^P$.

For $V_f < V_f'$, prestraining to $e_s$ will not develop the maximum compressive residual stress in the matrix, as shown in Figure 3a, since $e_s$ is limited by $\sigma_f^{max}$. Reloading the composite from $e_p$ results in stage I behavior up to a stress of $\sigma_I^P$ at a strain of $e_s = e_I^P$. The limited amount of prestrain due to the rapid approach of the fiber stresses to $\sigma_f^{max}$ therefore gives a relatively small effect of prestrain on the stage I yield stress for $V_f < V_f'$.

For $V_f > V_f'$, prestraining to $e_s$ (determined by $\sigma_f^{max}$) will cause compressive yielding in the matrix on unloading, with the development of a compressive residual stress in the matrix of $-\sigma_m^y$, as shown in Figure 3b. Actually, a prestrain of slightly less than $e_s$ would have been just as effective since yielding of the matrix on unloading does not affect $\sigma_I^P$ on reloading. On reloading from $e_p$, the stage I region extends almost to $e_s$ with $\sigma_I^P$ being considerably greater than $\sigma_I$.

Calculation of the Optimum Amount of Prestrain

The amount of prestrain necessary to get optimum elastic behavior in a given composite (maximum $\sigma_I^P$) is, therefore, determined by the properties of the fibers for $V_f<V_f'$ and by the matrix for $V_f>V_f'$. For $V_f<V_f'$, the maximum value of $\sigma_I^P$ is obtained from a prestrain of:

$$e_s = \frac{\sigma_f^{max} - \sigma_f^{RO}}{E_f} \qquad (5)$$

as can be seen from the geometry in Figure 3a. For $V_f>V_f'$, the maximum value of $\sigma_I^P$ is obtained from $e_s$ greater than the amount necessary to cause compressive yielding in the matrix on unloading. As can be seen from observing Figure 3b:

$$e_s^{min} = e_r + 2\sigma_m^y/E_m \qquad (6)$$

or

$$e_s^{min} = \frac{\sigma_f^R - \sigma_f^{RO}}{E_f} + \frac{2\sigma_m^y}{E_m} \qquad (7)$$

Using $\sigma_f^R$ obtained from the balance of forces (Equ. 2):

$$e_s^{min} = \frac{\sigma_m^y \cdot (1-V_f)}{E_f \cdot V_f} - \frac{\sigma_f^{RO}}{E_f} + \frac{2\sigma_m^y}{E_m} \tag{8}$$

The upper limit on $e_s$ may be defined in terms of $\sigma_f^{max}$, as was the case for $V_f < V_f'$, by Equ. 5. It should be noted that, for either $V_f < V_f'$ or $V_f > V_f'$, composites containing ductile fibers can be prestrained past $e_s$ defined by Equ. 5 without fracture, but no changes will occur in $\sigma_I^P$ (since strain hardening has been assumed to be negligible). On the other hand, composites containing brittle fibers will undergo fiber fracture if $e_s$ in Equ. 5 is exceeded. From a practical standpoint, $\sigma_f^{max}$ for brittle fibers should be taken as less than the fiber fracture stress in order to minimize the possibility of premature fiber failure.

Calculation of Residual Stresses Resulting from Prestraining

The present model can also be used to predict the residual stresses, $\sigma_m^R$ and $\sigma_f^R$, that were caused by the optimum amount of tensile prestraining. For $V_f < V_f'$, the elastic strains in the fibers and matrix on unloading after a prestrain $e_s$ given by Equ. 5 are equal (see Figure 3a). Therefore:

$$\frac{\sigma_f^{max} - \sigma_f^R}{E_f} = \frac{\sigma_m^y - \sigma_m^R}{E_m} \tag{9}$$

In addition, from the balance of forces after unloading:

$$\sigma_m^R \cdot (1-V_f) + \sigma_f^R \cdot V_f = 0 \tag{10}$$

Combining Equ. 9 and 10 yields:

$$\sigma_m^R = \frac{V_f \cdot (\sigma_m^Y \cdot \frac{E_f}{E_m} - \sigma_f^{max})}{1-V_f + V_f \cdot \frac{E_f}{E_m}} \tag{11}$$

and $$\sigma_f^R = \frac{(\sigma_m^y \cdot \frac{E_f}{E_m} - \sigma_f^{max}) \cdot (V_f - 1)}{1 - V_f + V_f \cdot \frac{E_f}{E_m}} \tag{12}$$

For $V_f > V_f'$, the residual stress in the matrix after the optimum amount of prestrain ($e_s$ between the values given by Equ. 8 and Equ. 5) is $-\sigma_m^y$. From the balance of forces given by Equ. 2:

$$\sigma_f^R = \frac{\sigma_m^y \cdot (1-V_f)}{V_f} \tag{13}$$

It should be recognized that Equ. 9 through 13 are independent of $\sigma_m^{RO}$ and $\sigma_f^{RO}$.

Calculation of $\sigma_I^P$ Resulting from the Optimum Prestraining

The maximum values of $\sigma_I^P$ are developed by the optimum amount of prestrain. For $V_f < V_f'$, it may be seen from Figure 3a and the rule-of-mixtures that:

$$\sigma_I^P = \sigma_m^y \cdot (1-V_f) + \sigma_f^{max} \cdot V_f \tag{14}$$

For $V_f = V_f'$, stage II deformation behavior (one component plastic, the other elastic) will be eliminated by the prestrain. The composite will either fracture at $\sigma_I^P$ (for brittle fibers) or will proceed from stage I to stage III (both components deforming plastically) at $\sigma_I^P$. For $V_f > V_f'$, the geometry of Figure 3b and the rule-of-mixtures give:

$$\sigma_I^P = \sigma_m^y \cdot (1-V_f) + (\frac{2\sigma_m^y}{E_m} \cdot E_f + \sigma_f^R) \cdot V_f \tag{15}$$

Using Equ. 13 for $\sigma_f^R$ and simplifying:

$$\sigma_I^P = 2\sigma_m^y \, (1-V_f + V_f \cdot \frac{E_f}{E_m}) \tag{16}$$

Stresses greater than those given by Equ. 16 will provide stage II deformation and, ultimately, fracture for brittle fibers or stage III for ductile fibers. The extent of stage II deformation increases with the departure of $V_f$ from $V_f'$.

It is useful to compare the $\sigma_I^P$ values from Equ. 14 ($V_f<V_f'$) and Equ. 16 ($V_f>V_f'$) to those which would be obtained without intentional prestraining. The rule-of mixtures indicates that:

$$\sigma_I = \sigma_m^y \cdot (1-V_f) + (\sigma_f^{RO} \cdot V_f) + \frac{\sigma_m^y - \sigma_m^{RO}}{E_m} \cdot E_f \cdot V_f \qquad (17)$$

for all values of $V_f$. Applying the balance of forces:

$$\sigma_m^{RO} \cdot (1-V_f) + (\sigma_f^{RO} \cdot V_f) = 0 \qquad (17)$$

and simplifying yields:

$$\sigma_I = (\sigma_m^y - \sigma_m^{RO}) \cdot (1-V_f + V_f \cdot \frac{E_f}{E_m}) \qquad (18)$$

It is noteworthy that $\sigma_I$ may vary from zero ($\sigma_m^{RO} = \sigma_m^y$) to a maximum for $\sigma_m^{RO} = -\sigma_m^y$, the situation intentionally achieved by prestraining for $V_f>V_f'$ as given by Equ. 16. If $\sigma_m^{RO} = 0$, comparison of Equ. 18 and 16 indicates that, for $V_f>V_f'$, optimum prestraining results in a factor of two increase in the first stage yield point ($\sigma_I$ to $\sigma_I^P$). If $\sigma_m^{RO}$ is positive, the increase in the first stage yield point due to prestraining can be even larger than a factor of two.

A graphical description of the effects of $V_f$, $E_m$, $E_f$, $\sigma_m^y$, and $\sigma_m^{RO}$ on the values of $\sigma_I$ (Equ. 18) is given in Figure 4. Figure 5 gives the dependence of the optimum $\sigma_I^P$ ($V_f<V_f'$) from Equ. 14 on $\sigma_m^y$, $V_f$, and $\sigma_f^{max}$. The dependence of the optimum $\sigma_I^P$ ($V_f>V_f'$) from Equ. 16 on $\sigma_m^y$, $V_f$, $E_f$, and $E_m$ is given in Figure 4 for $(\sigma_m^y - \sigma_m^{RO})/\sigma_m^y = 2$, that is $\sigma_m^{RO} = -\sigma_m^y$ due to the optimum prestrain.

## EXPERIMENTAL PROCEDURE

The preceding analysis was evaluated experimentally on composites of tungsten wires (0.005 in. diameter) in 2024 aluminum matrices. The aluminum-tungsten system

was chosen because of ease of fabrication by filament winding and hot pressing, past experience with the system (7-9), and suitable mechanical properties of the component materials to give a reasonable test of the analysis. The critical volume fraction for this sytem was $V_f' = 0.213$ (Equ. 4), using the following values determin previously (7-9):

$$E_m = 10 \times 10^6 \text{ psi.}$$
$$E_f = 55 \times 10^6 \text{ psi.}$$
$$\sigma_m^y = 17 \times 10^3 \text{ psi. (annealed)}$$
$$\sigma_f^y = 250 \times 10^3 \text{ psi.}$$

These values can also be used to define the optimum prestrain for the system using Equ. 5 and 8 and assuming that the residual stresses in the composites prior to prestraining are negligible. For $V_f < V_f' = 0.213$, $e_s = 4.5 \times 10^{-3}$, independent of the value of $V_f$. For $V_f > V_f' = 0.213$, $e_s^{max} = 4.5 \times 10^{-3}$ with $e_s^{min}$ decreasing with increasing $V_f$ (for $V_f = 0.30$, $e_s^{min} = 4.1 \times 10^{-3}$; for $V_f = 0.40$, $e_s^{min} = 3.9 \times 10^{-3}$).

A series of 2024 aluminum-tungsten composites were fabricated having fiber volume fractions of 0.08, 0.13, 0.20, 0.30, and 0.40. Filament winding was carried out on a flat mandrel using a lathe to turn the mandrel and wind the tungsten wire. Six layers of wire (seven layers of 2024 aluminum foil) were used in the $V_f = 0.20$, 0.30, and 0.40 composites; four layers of wire were used in the $V_f = 0.08$ and 0.13 composites. The hot pressing was carried out at 950°F for 2 hours in vacuum with the foil-wire layup fastened to the winding mandrel. The initial bonding pressure was 2000 psi.; after a short dwell time (a few minutes), the pressure was reduced to 500 psi. for the remainder of the pressing operation. The resulting composites were approximately 2 in. x 4 in. x 0.05 in. thick. Metallographic observation of the composites indicated that the actual volume fractions of tungsten were within about one percent of the nominal values. Typical microstructures are shown in Figure 6.

Flat tension test specimens with 0.5 in. gage lengths were prepared from the composite plates by grinding with a contoured grinding wheel. Strain gages were attached to each specimen in order to provide accurate measurements of strain during tension testing and to facilitate precise determination of the amount of prestrain. One series of specimens (all five volume fractions) were tension tested on an Instron machine at a strain rate of $4x10^{-3}min.^{-1}$ with the load being recorded in strain increments of $10^{-4}$. A second series was prestrained $4.2x10^{-3}$, unloaded, and then tension tested in the same manner as the first series. The amount of prestrain was slightly less than the optimum predicted by the analysis in order to minimize the possibility of yielding the tungsten fibers. It was recognized that residual stresses would probably be present in the as-fabricated composites, leading to some loss of precision in the optimum prestrain calculation.

## EXPERIMENTAL RESULTS

The prestrained tension test specimens exhibited stage I yield stresses, $\sigma_I^P$, which were considerably greater than those of the as-fabricated specimens, $\sigma_I$. These data are shown in Figure 7 which indicates only the initial regions of the stress-strain curves of both series' of composites; $\sigma_I^P$ and $\sigma_I$ values are marked as open circles. Also shown in Figure 7 are the theoretical maximum values of $\sigma_I^P$ (closed circles) as calculated from Equ. 14 for $V_f<V_f' = 0.213$ and Equ. 16 for $V_f>V_f' = 0.213$. The close approach of the experimental values of $\sigma_I^P$ to those calculated from the analysis is considered to be strong support for the utility of the analysis.

As was pointed out previously in connection with Equ. 18, optimum prestraining can double the stage I yield stresses of as-fabricated composites having negligible residual stresses. The data in Figure 7 show increases in $\sigma_I$ in some instances

by a factor of about six, indicating that prestraining is an effective means of also removing the deleterious effects of residual stresses which are unfavorable for the type of stress that is to be imposed on the composites. Evidently, the as-fabricated composites in the present study had positive residual stresses in the matrix prior to testing, a condition favorable for compressive loading, not tensile. Such tensile matrix residual stresses are to be expected from the differences in coefficients of thermal expansion between aluminum and tungsten, and should be common in composites having high modulus fibers.

It should also be observed that stage I yield stresses of the as-fabricated composites ($\sigma_I$) behaved in a non-regular manner as a function of $V_f$. It is presumed that this results from the fact that it is difficult to control the state of residual stress in hot pressed composites. Prestraining may be of use in offsetting such variability.

## DISCUSSION

The analysis of the effect of prestraining composites, although evaluated experimentally on just one type of system, should be applicable to a variety of different types of composites designed for uses which require a large stage I tensile yield strength. (Furthermore, even though the experiments of the present study were carried out on hot pressed composites, the effects demonstrated in this study should be applicable to composites fabricated by other techniques.) For applications which require a large stage I compression yield strength, residual stresses developed on cooling (tensile in the matrix) due to differences in thermal expansion of the matrix and fiber should provide improved performance over composites without residual stresses. Care must be taken in the use of composites under cyclic stress conditions. If the magnitudes of the tensile and compressive stresses are the same during cyclic loading, prestraining can be used to obtain an initial state of zero residual stress which would then minimize the chance of yielding in either

tension or compression.

The prestraining effects may also be applied to improving the performance of composites used to restrain static bending forces under conditions where plastic deformation is to be avoided. If a beam were constructed such that a tension-prestrained composite was fastened to the surface subjected to tension and an as-fabricated composite (assuming tensile residual stresses in the matrix) was fastened to the surface subjected to compression, the resulting beam would be capable of withstanding much higher bending forces than a normal composite material beam. Similar advantages could be achieved for plate structures by using this concept.

The prestraining concept could also be used to lower the cost of composites by lowering the amount of expens[illegible] fiber material necessary to achieve a given stage I yield stress under conditions where a lower elastic modulus could be tolerated. For example, the materials cost in 2024 aluminum-boron composites is determined primarily by the amount of boron. Rule-of-mixtures calculation of $\sigma_I$ using Equ. 18, assuming negligible residual stresses, is given in Figure 8 as a function of the volume fraction of boron. The values of $\sigma_I^P$ calculated for the optimum prestrain from Equ. 16 for $V_f > V_f = 0.102$ are twice the values of $\sigma_I$ as discussed previously. Figure 8 shows that stage I yield stresses in as-fabricated composites of $V_f = 0.50$ ($\sigma_I = 60{,}000$ psi.) can be achieved in prestrained composites using $V_f = 0.20$, a saving in boron content of 60%. This comparison would be even more striking for as-fabricated composites containing the usual tensile residual stresses in the matrix and having lower values of $\sigma_I$ than those indicated in Figure 8.

## SUMMARY

The effect of prestraining on the stage I yield stress of composites which obey the rule-of-mixtures has been analyzed in terms of the properties of the matrix and fiber materials The improvement in the stage I tensile yield stress due to tensile prestraining results from the development of a maximum compressive residual stress in the matrix upon unloading of composite following prestraining. Knowledge of the yield strengths, as-fabricated residual stresses, volume fractions, and moduli of the matrix and fiber materials (and fracture strength of brittle fibers) permits calculation of the amount of prestrain necessary and the magnitude of the residual stresses and stage I yield stress resulting from prestraining. The analysis should be of value in improving the performance of composites in a variety of applications where a large range of tensile elastic behavior, i.e., high stage I tensile yield stress, is critical to composite performance.

## ACKNOWLEDGEMENTS

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## LIST OF FIGURE CAPTIONS

Figure 7. Initial regions of stress-strain curves for both as-fabricated and prestrained composites (marked P; $e_s = 4.2 \times 10^{-3}$) ranging from $V_f = 0.08$ to 0.40. Experimental $\sigma_I$ and $\sigma_I^P$ values indicated by open circles; $\sigma_I^P$ values calculated from the analysis assuming optimum prestrain indicated by closed circles.

Figure 8. Calculated values of $\sigma_I$ and $\sigma_I^P$ for 2024 aluminum-boron composites using the analysis of the present study. $\sigma_I$ values calculated assuming negligible residual stresses in as-fabricated composites.

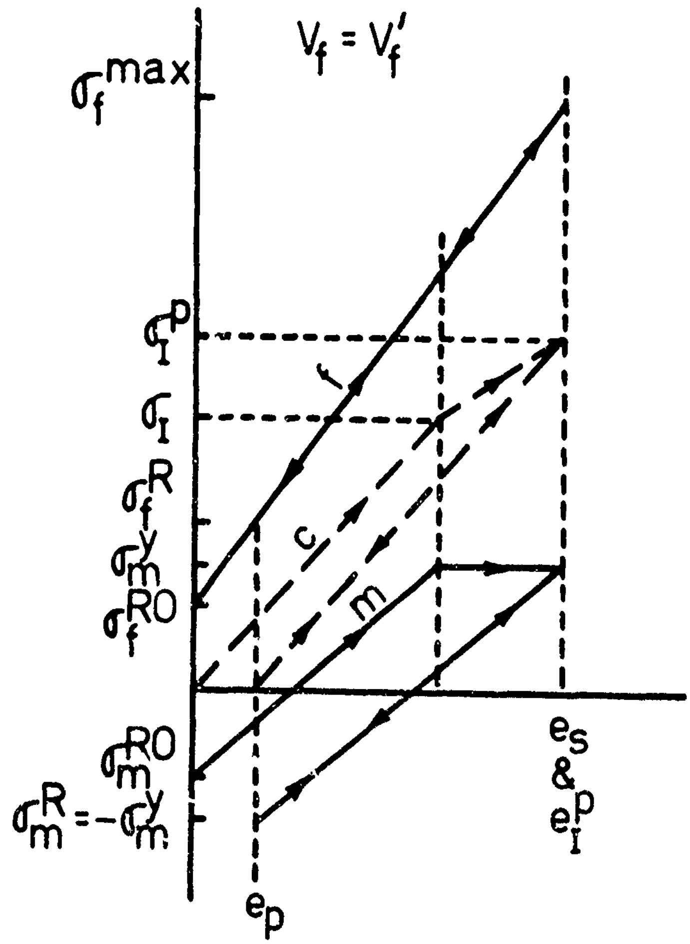



Figure 1. Schematic representation of a load-unload-reload cycle for the prestraining and testing of a composite of critical fiber content, $V_f$. The composite stress-strain curve, c, is determined by the rule-of-mixtures addition of the matrix, m, and fiber, f, curves.

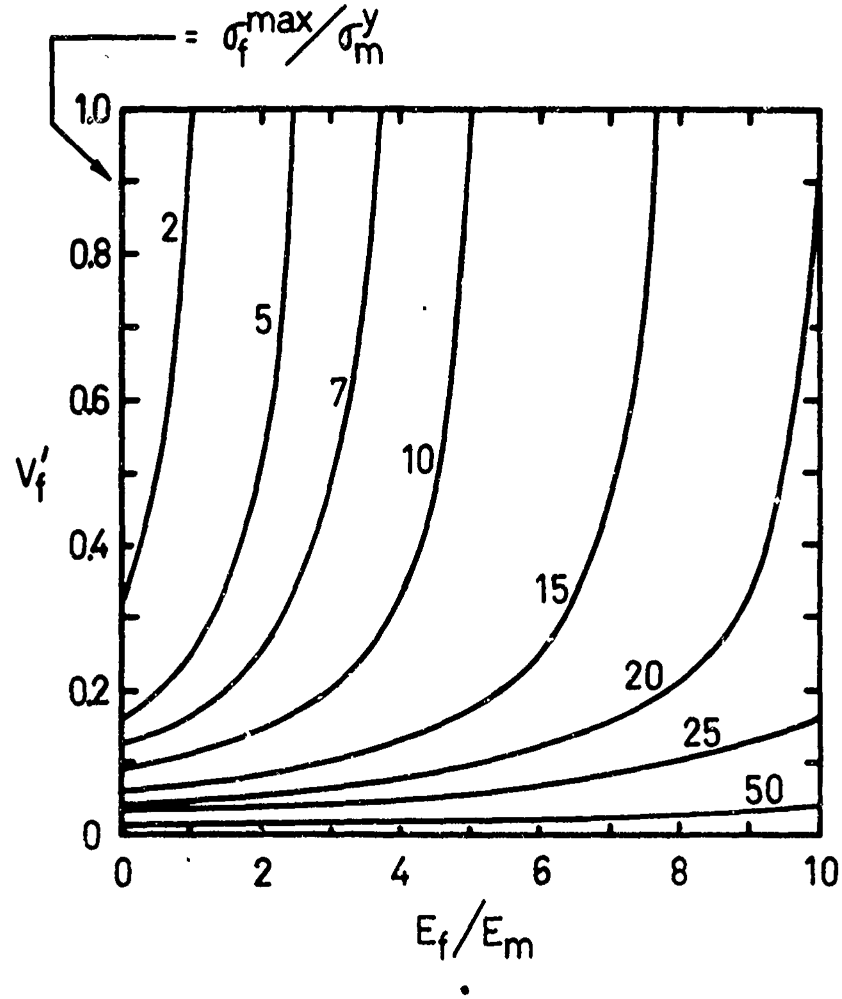



Figure 2. Graphical representation of the critical volume fraction, $V_f'$, in terms of matrix and fiber mechanical properties.

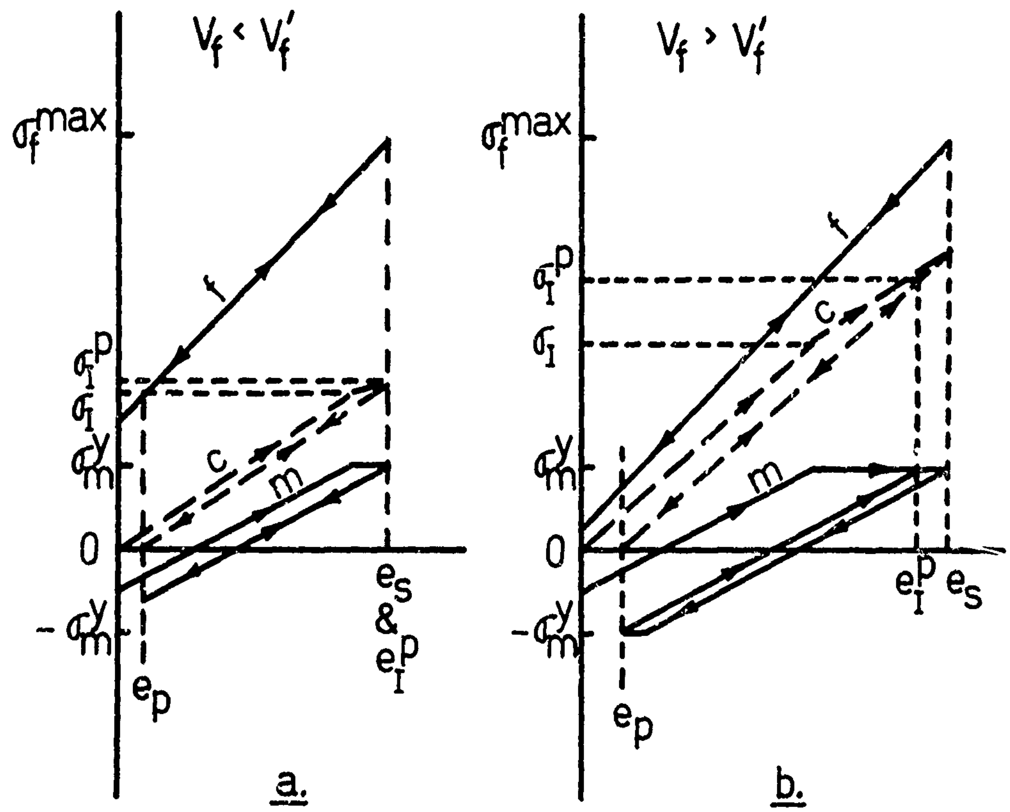



Figure 3. Schematic representation of load-unload-reload cycles for the prestraining and testing of composites having $V_f<V_f'$ (a) and $V_f>V_f'$ (b). The composite stress-strain curves, c, are determined by the rule-of-mixtures addition of the matrix, m, and fiber, f, curves.

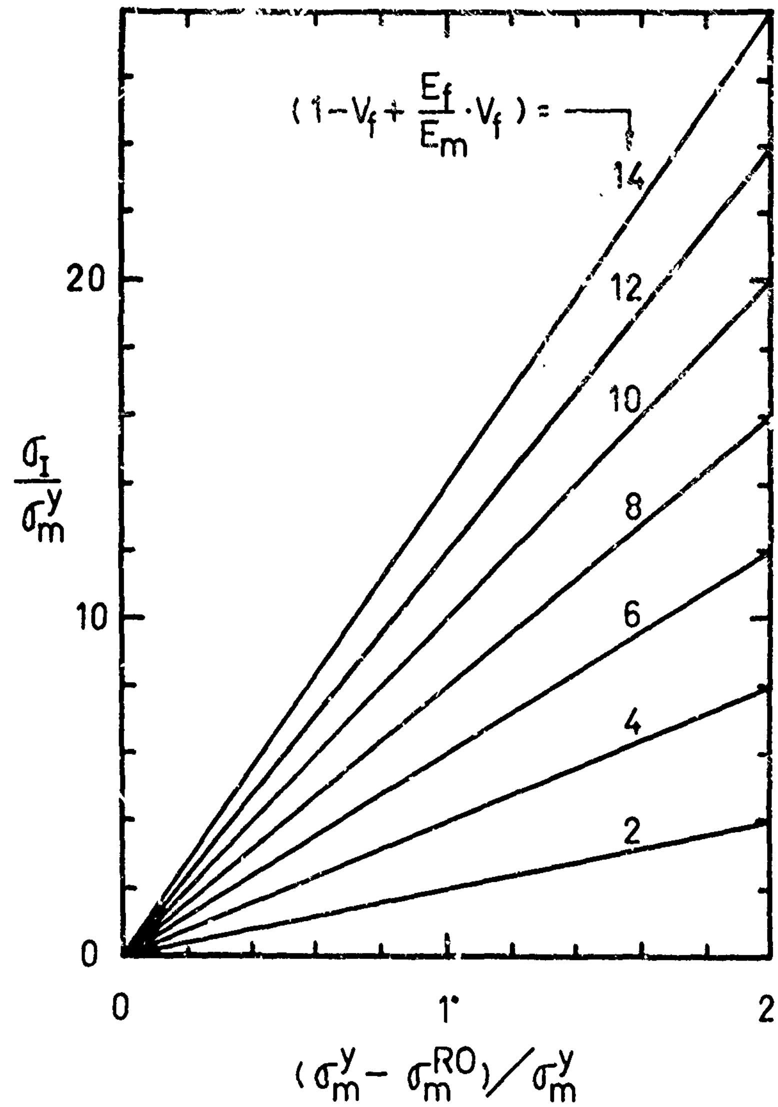



Figure 4. Graphical representation of the stage I yield stress for as-fabricated composites, $\sigma_I$, in terms of matrix and fiber properties and fiber volume fraction. The value of $\sigma_I^p$, the stage I yield stress after the optimum prestrain, for $V_f > V_f'$ may also be determined from this graph as the value of $\sigma_I$ for $(\sigma_m^y - \sigma_m^{RO})/\sigma_m^y = 2$.

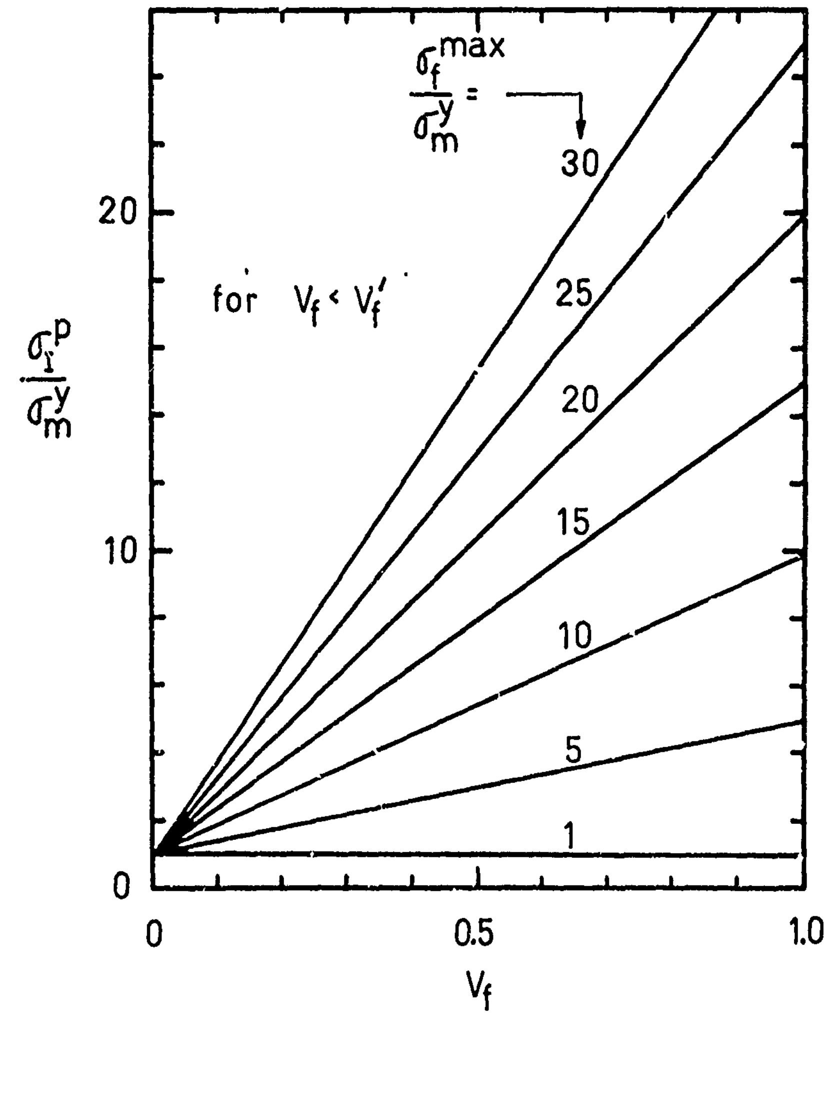



Figure 5. Graphical representation of the stage I yield stress after optimum prestrain, $\sigma_I^p$, for $V_f<V_f'$ in terms of matrix and fiber properties and fiber volume fraction.

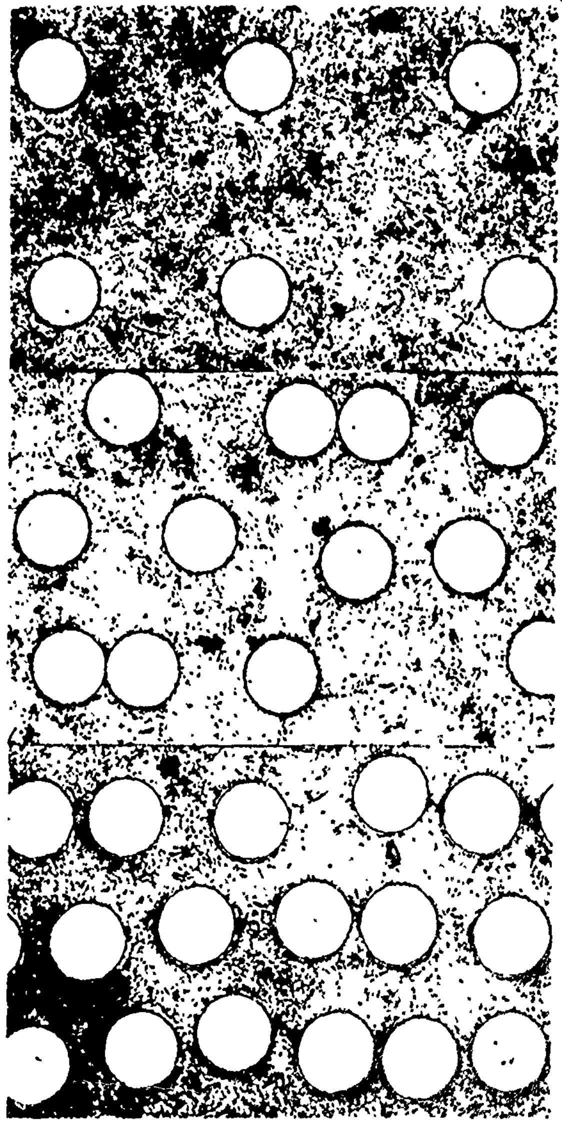
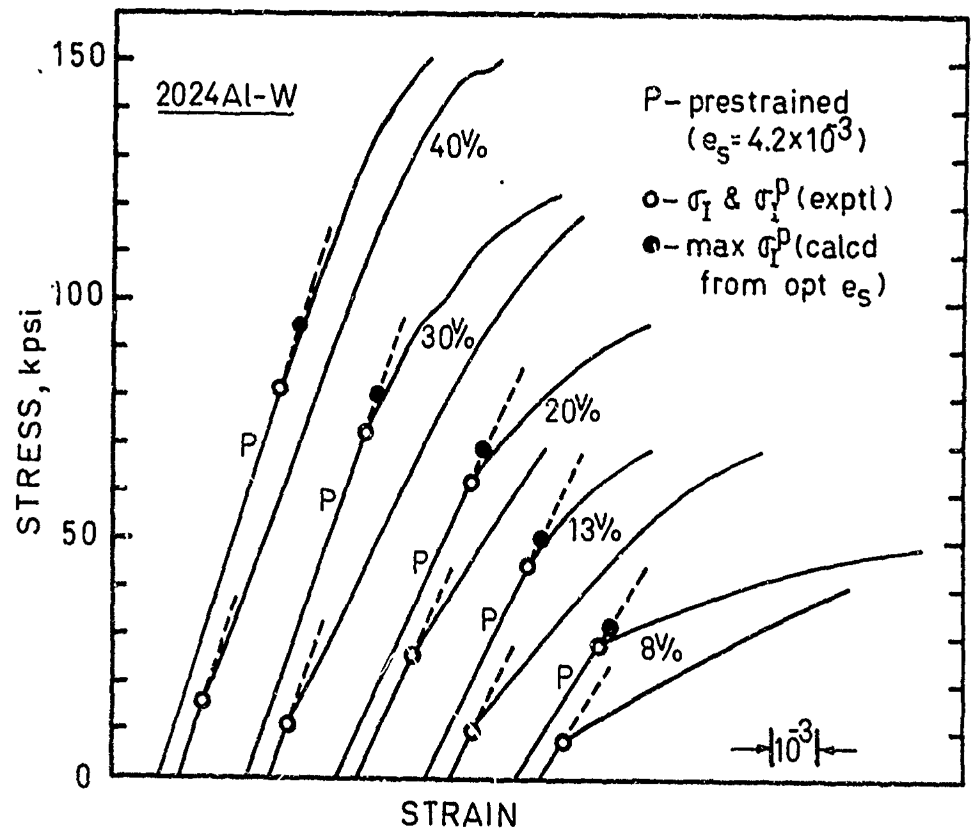


Figure 6. Photomicrographs of typical 2024 aluminum-tungsten composites used in the present investigation. a. $V_f = 0.08$, b. $V_f = 0.20$, c. $V_f = 0.40$. 75x

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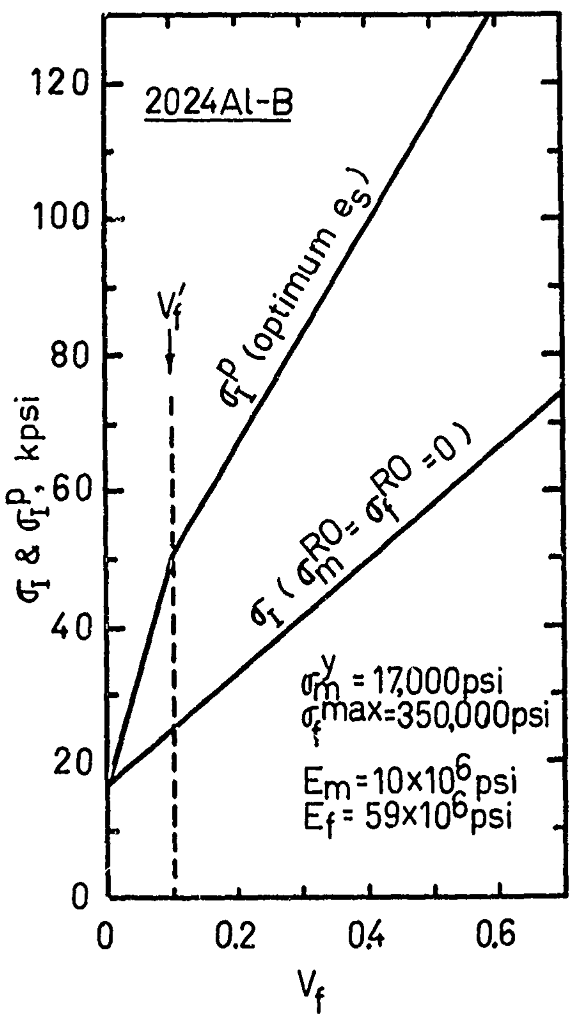


Figure 8. Calculated values of $\sigma_I$ and $\sigma_I^p$ for 2024 aluminum-boron composites using the analysis of the present study. $\sigma_I$ values calculated assuming negligible residual stresses in as-fabricated composites.